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THE EFFECT OF WAVE IMPEDANCE ON HUMAN WHOLE-BODY RADIOFREQUENCY ABSORPTION RATES

by

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ABSTRACT

Human volunteers were exposed to low level radiofrequency (RF) radiation inside a very large TEM cell. The wave impedance of the exposures was varied by using a number of standing wave patterns created by different mismatched loads on the cell. The method works best for the E orientations and is limited to $1/2 < E/(377H) < 2$. The fraction of the RF absorption rate attributable to each of the electric and magnetic fields is determined by a graphical method. For the E orientations and frequencies from 7.00 to 40.68 MHz, over 90 percent of the RF absorption rate (on average) was attributable to the electric field. This result applies to both E orientations (EKH and EHK) under both free-space and grounded conditions. It also agrees with the quasi-static calculation for the prolate spheroid model of a human.

RÉSUMÉ

Des volontaires humains ont été exposés à des rayonnements radiofréquences (RF) de faible niveau dans une cellule TEM de très grande dimension. Des ondes d'impédance variable ont été produites par l'utilisation d'un certain nombre de réseaux d'ondes stationnaires formés au moyen de charges non adaptées à la cellule. Avec cette méthode, les meilleurs résultats sont obtenus dans les directions E; la méthode est limitée à la plage $1/2 < (E/377H) < 2$. La proportion du taux d'absorption RF attribuable au champ magnétique ou au champ électrique est déterminée graphiquement. Pour les directions E et les fréquences de 7.00 à 40.68 MHz, plus de 90% du taux d'absorption RF (en moyenne) était attribuable au champ électrique. Ces résultats s'appliquent aux deux directions E (EKH et EHK) dans les conditions d'espace libre et de contact avec la terre. De plus, les résultats concordent avec les calculs quasi-statiques pour la modélisation d'un être humain par un sphéroïde allongé.

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INTRODUCTION

Current radiofrequency (RF) radiation safety standards (eg. ANSI, 1982 [1]) are based, in part, on assumed rates of human whole-body RF absorption. The absorption rates for actual human subjects have only recently been reported by our group [2]. For technical reasons our measurements are limited to the frequency range of 3 to 41 MHz.

The first report [2] was restricted to determining the effect of frequency and grounding on the whole-body absorption rates for simulated far-field exposure conditions. It is well known, however, that most occupational exposures occur in the near field of the RF source. In the near field, the wave impedance (E/H) is often significantly different from the far-field value of 377 Ω [3,4]. With our exposure apparatus - a very large TEM cell - we can vary the wave impedance and thus simulate one important aspect of near-field exposures.

The basic method of varying the wave impedance is to use a set of mismatched loads on the end of the TEM cell to produce different standing-wave patterns inside the cell. By selecting an appropriate load and longitudinal position within the cell, it is theoretically possible to produce any wave impedance. Practical limitations on the achievable range of wave impedance are discussed below. The method applies equally well to the simulation of both free space and grounded conditions. All measurements were performed in the modified version of the TEM cell [5], in which all TE resonances were suppressed.

METHODS

All volunteers were adult males in good health. Exposures were limited to one hour per day at a power density not exceeding 20 $\mu W\ cm^{-2}$. No subject ever absorbed at a rate exceeding 1 watt.

The orientation of the subject's body with respect to the simulated plane wave is denoted by the usual ellipsoid-equivalent notation [6; pp. 11-13]. Thus, for example, in the EKH orientation, E is parallel to the body length, K is in the shoulder-to-shoulder direction, and H is in the front-to-back direction.

Absorbed-power measurements were performed with the system described previously [7]. To compensate for the use of a mismatched load, two minor changes were made in the method. First, a 6 dB attenuator was used between the source and the cell to provide 12 dB of isolation to the generator. Secondly, the parameter α, used for computing absorbed power [7; eq (2)] by taking into account reflections from the load, was set to a different value for each load.

The effect of different loads on the wave impedance inside the cell is shown in Fig. 1. The results are expressed in terms of the normalized wave impedance, η, defined as

$$\eta = (E/H)/377\Omega \qquad (1)$$

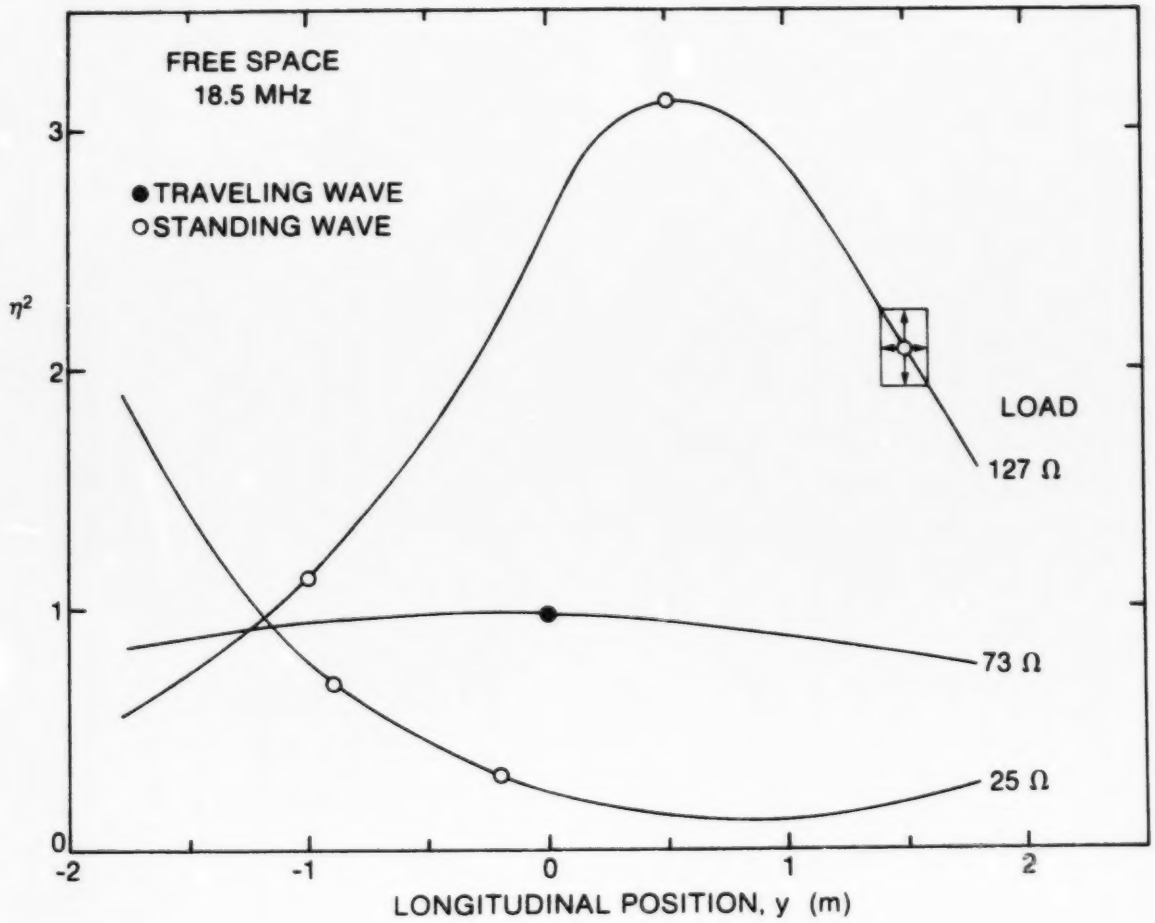

FIGURE 1 - THE DEPENDENCE OF SQUARED NORMALIZED WAVE IMPEDANCE (η^2) ON BOTH LOAD RESISTANCE AND LONGITUDINAL POSITION IN THE TEM CELL. THE CELL CENTER IS AT y = 0.

Eta is dimensionless and is equal to unity for free space. η^2 is plotted in the figure since that is the quantity used in the theoretical analysis.

It can be seen in Fig. 1 that practically no standing wave is created inside the cell when a 73-Ω load, which nearly matches the 70-Ω cell, is employed. In this case, the subject is essentially exposed to a travelling wave. On the other hand, when a mis-matched load is employed, the subject is exposed to a standing wave pattern, with a wave impedance depending strongly on both load resistance and longitudinal position in the cell. The points marked on the curves are the actual combinations of load and position employed in these experiments. Thus, six different values of η^2, ranging from 0.30 to 3.1, were employed at 18.5 MHz.

The method is limited by three practical problems: (1) field measurement errors; (2) the finite size of the body compared to a wavelength; and (3) sensitivity limitations for the weakly-absorbing orientations.

Inaccuracies in field measurements result in a large possible error in η whenever either E or H is very small. This excludes the use of extreme values of η. The range normally used for η^2 was 0.25 to 4.0; η^2 was never used outside the range of 0.20 to 5.0.

The finite size of the body compared to a wavelength causes one side of the body to be exposed to a different value of η^2 than the other side. For a subject in an EKH orientation, this effect is illustrated (in Fig. 1) by the point inside the box on the 127-Ω curve. The horizontal arrows indicate that for this orientation the average width of the body is about 20 cm. The vertical arrows show the range of η^2 across the body which results from its finite width and the slope of the curve.

The third problem is the limited sensitivity of the absorbed-power measurement system. For example, the absorption rates for the H orientations are so small that an accurate measurement is only possible for the HEK orientation, and only at the highest operating frequency, 40.68 MHz (an ISM frequency). For the HEK orientation, the finite body size is not a problem.

For both E orientations (EKH and EHK) neither the body size nor the system sensitivity were a problem. Accurate results were obtained for both E orientations from 13.56 to 40.68 MHz. For the grounded case, the results could also be extended to 7.00 MHz.

For the K orientations, both body size and system sensitivity are limiting factors. System sensitivity precludes measurements below 18.50 MHz and the finite body size precludes measurements above that frequency. Even at 18.5 MHz, the body length is 0.11λ in comparison to the spacing of 0.25λ between successive minima and maxima of the standing wave pattern. Even by placing the body at the optimum position (y = 0.6 m in Fig. 1), which is at an extremum of the standing wave pattern, the variation in η^2 over the length of the body is still 50 percent.

In summary, because of the limitations in the method, the effect of wave impedance could only be determined at 40.68 MHz for the H orientation

and at 18.5 MHz for the K orientation. The complete frequency range of 7.00 to 40.68 MHz could be studied for the E orientation.

THEORY

The whole-body absorption rate of a human subject, A_s, will be assumed to be related to the two exposure fields, E and H, by the equation

$$A_s = aE^2 + bH^2 \quad ; \quad a, b > 0 \tag{2}$$

In (2), A_s is expressed in watts, E in rms V/m, and H in rms A/m. This equation will be shown to fit almost all the human data. It is also identical to the theoretical result for the long-wavelength conductor model of the prolate spheroid [8]. The equation also has the advantage that it can be directly applied to near-field exposure problems, in which both E and H are determined.

The basic equation can be transformed into a more useful form by replacing the two parameters, a and b, by two new parameters, c and x, and using (1). The results is

$$A_s/H^2 = c[x\eta^2 + (1 - x)] \tag{3}$$

It is easily shown that $c(1 - x) = b$ and $cx = 377^2a$. Furthermore, since a, $b > 0$, we have $c > 0$ and $0 < x < 1$.

The transformed equation has a simple interpretation. By comparing it with the first equation it is easily seen that x is the fraction of the absorbed power attributable to the electric exposure field and $(1 - x)$ is the fraction attributable to the magnetic exposure field. Furthermore, the RHS of (3) with $x = 0.5$ is nothing more than the well-known formula for the density of stored electromagnetic energy in air or vacuum:

$$(\text{Stored energy density})/H^2 = c[0.5\ \eta^2 + 0.5] \tag{4}$$

Thus, E and H are equally important as far as the energy stored in the exposure fields is concerned. The relative importance of E and H to the human whole-body absorption rate must be found by determining x for each body orientation and frequency.

x is determined by applying (3) to a graph of A_s/H^2 vs η^2. The general plotting scheme is illustrated in Fig. 2. If (3) is valid, the plot of the data will be a straight line within the shaded area. If the absorption rate depends entirely on $E^2(x = 1)$ the plot will be a straight line through the origin. On the other hand, if the absorption rate depends on $H^2(x = 0)$, the graph will be a horizontal straight line. If the graph turns out to be a straight line not within the shaded area, or any curved line, then the theory is invalid.

$$A_S/H^2 = c[X\eta^2 + (1-X)]$$

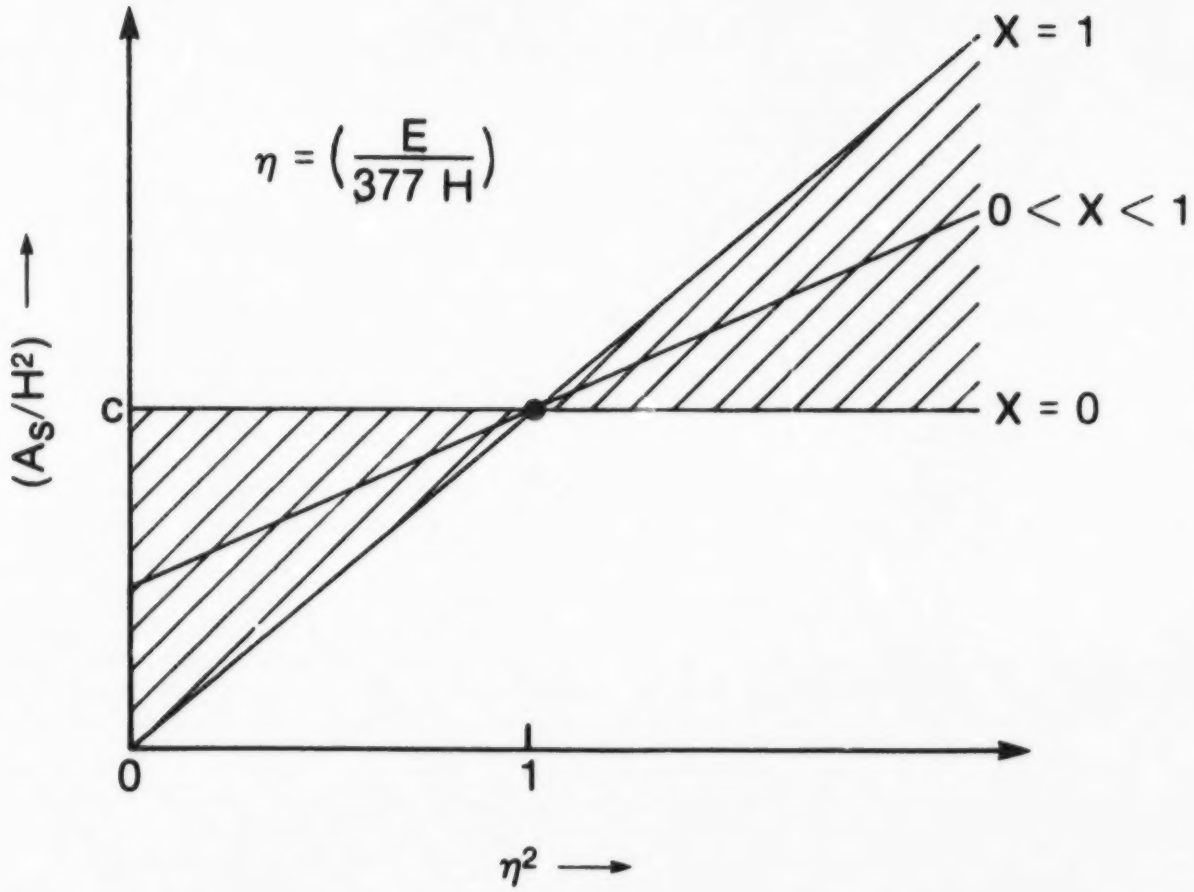

FIGURE 2 - GENERAL PLOTTING SCHEME FOR THE COMPARISON OF THEORY AND MEASUREMENTS.

RESULTS

Typical results are presented in Figs. 3 and 4 for subject F exposed in an EKH orientation at 18.5 MHz under both free-space and grounded conditions. The horizontal arrows simply indicate the spread in wave impedance over the finite size of the body, as explained in connection with Fig. 2. The value of x is determined by a linear regression analysis. The error estimate given for x is essentially the standard error of estimate for the regression line. It can be seen that for the data of Figs. 3 and 4, x is not statistically significantly different from unity.

The regression lines are only fit to the data points determined with the standing-wave patterns. It may be seen, however, that the one data point determined for a traveling wave lies on the same straight line. Thus, the E-polarization absorption rate for $\eta = 1$ is independent of whether or not the exposure is one-sided or two-sided. This result is to be expected for quasi-static frequencies and was assumed to be the case in the theoretical treatment of the prolate spheroid model.

The results for four different subjects in an E orientation at one frequency are compared in Table 1.

It can be seen in Table 1 that x is close to unity in almost every case. Twelve of the fourteen values of x in the table are between 0.9 and 1.1. Furthermore, the average value of x for all the data is 1.00 ± 0.03 ($N = 14$). Finally, the values of x do not appear to depend on subject, grounding, or which of the two possible E orientations is employed.

The fact that x is close to unity means that almost all of the absorption is due to the electric exposure field and very little is due to the magnetic exposure field.

Because the results of Table 1 do not depend on the subject, and because the available time with the volunteers was limited, the remaining experiments were all performed only on subject M.

The frequency-dependence of the wave impedance effect on subject M in the E orientation is shown in Table 2. The relatively large values of Δx for the bottom figures in each column are due to the effect of noise: plots of the data show scatter about a straight line, not any tendency to curve. The sensitivity limit of the system did not permit a reliable free-space measurement at 7 MHz.

For both the free-space and grounded cases, the values of x are independent of which E orientation is employed. For the grounded case, all values of x are between 0.93 and 1.05, and the average value of x is virtually unity (0.99 ± 0.01).

The free-space results depend on frequency. The average value of x, 0.89 ± 0.05 (8), is significantly less than unity ($p = 0.05$, 1-tailed t test). The value of x at 13.56 MHz ($x = 0.75$) suggests that the similar result for subject K at a slightly higher frequency (in Table 1) may be a real effect and not just a statistical fluctuation. Sensitivity limitations unfortunately prevent the determination of x at frequencies below 13.56 MHz.

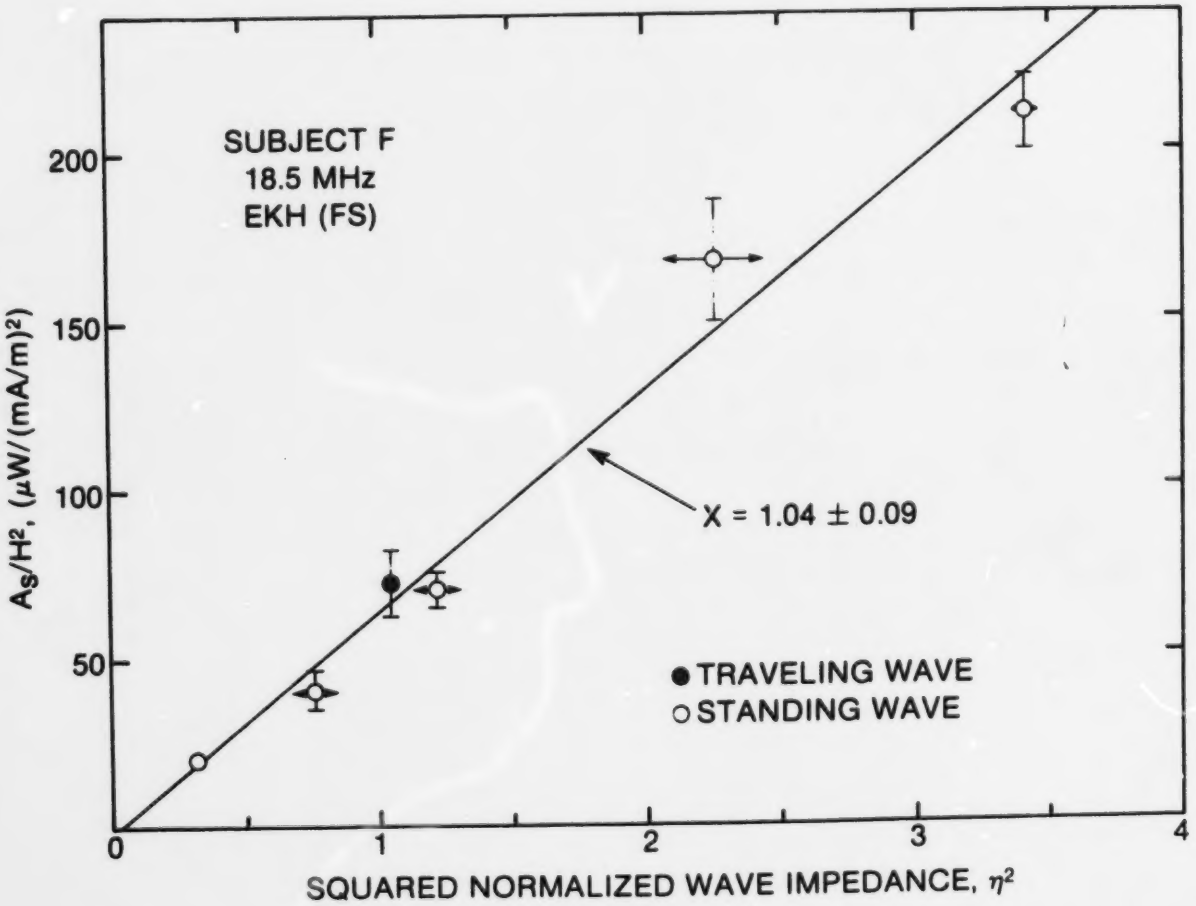

FIGURE 3 - WAVE-IMPEDANCE ANALYSIS OF THE FREE-SPACE ABSORPTION DATA FOR SUBJECT F IN AN EKH ORIENTATION AT 18.5 MHz.

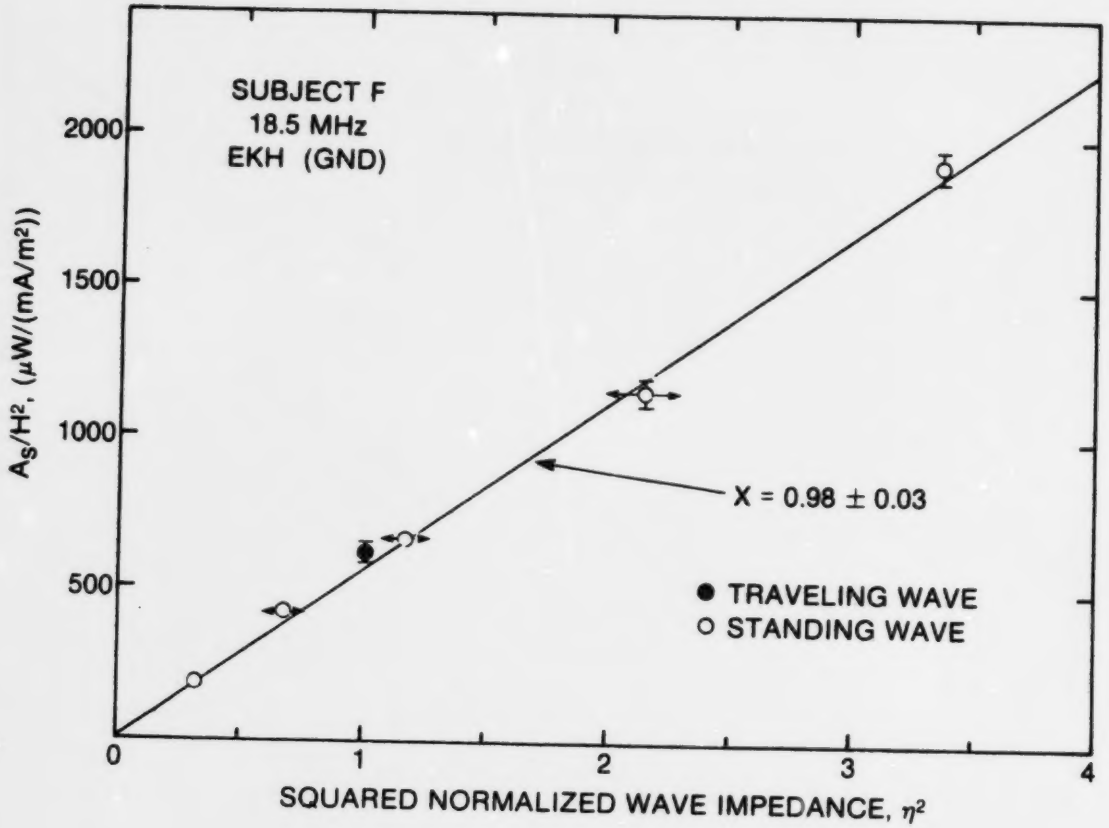

FIGURE 4 - WAVE-IMPEDANCE ANALYSIS OF THE GROUNDED ABSORPTION DATA FOR SUBJECT F IN AN EKH ORIENTATION AT 18.5 MHz.

TABLE 1

EFFECT OF WAVE IMPEDANCE ON THE E-POLARIZATION ABSORPTION RATES OF FOUR DIFFERENT SUBJECTS AT 18.5 MHz

SUBJECT	$x \pm \Delta x$			
	Free Space		Grounded	
	EKH	EHK	EKH	EHK
F	1.04 ±0.09	1.00 ±0.08	0.98 ±0.03	0.99 ±0.03
I	0.96 ±0.05	1.21 ±0.05	1.04 ±0.01	1.07 ±0.01
K	0.74 ±0.07	a	1.08 ±0.05	a
M	1.03 ±0.05	0.97 ±0.10	0.95 ±0.02	0.97 ±0.01

a. Subject no longer available.

Subjects range in mass from 71 to 83 kg, and in height from 171 to 180 cm.

TABLE 2

EFFECT OF WAVE IMPEDANCE ON THE E-POLARIZATION ABSORPTION RATE OF SUBJECT M AT DIFFERENT FREQUENCIES

FREQUENCY (MHz)	$X \pm \Delta X$			
	Free Space		Grounded	
	EKH	EHK	EKH	EHK
40.68	0.77 ±0.03	0.85 ±0.03	0.94 ±0.01	0.97 ±0.01
23.25	0.97 ±0.03	1.07 ±0.09	1.01 ±0.02	1.00 ±0.02
18.5	1.03 ±0.05	0.97 ±0.10	0.95 ±0.02	0.97 ±0.01
13.56	0.72 ±0.03	0.75 ±0.29	0.98 ±0.02	1.04 ±0.07
7.0	-		1.03 ±0.20	1.04 ±0.11
mean ± SE	0.89 ± 0.05 (8)		0.99 ± 0.01 (10)	

Subject M: height, 171 cm; weight, 71 kg.

For the HEK orientation, the value of x can only be determined at 40.68 MHz, as previously explained. The plot for subject M is shown in Fig. 5. The value of x, 0.51 ± 0.06 is clearly different from any result for an E orientitation.

For the KEH orientation, only a frequency of 18.5 MHz is usable. The results for subject M at that frequency are presented in Fig. 6. The regression line is clearly not a good fit to the data. It may be that the simple theory does not apply to the K orientation. On the other hand, the experimental method is least exact for this orientation, since η^2 varies 50 percent over the length of the body.

DISCUSSION

Summary of Results

The effect of wave impedance on human whole-body RF absorption rates has been studied experimentally for the first time. The variation of the normalized wave impedance, η, from the free-space value of unity simulates one aspect of near-field RF exposures. The method is limited to values of η within the range $0.5 < \eta < 2$ ($0.25 < \eta^2 < 4$).

Substantial results were only obtainable for the two E orientations. Results for the EKH orientation were indistinguishable from those for the EHK orientation. The parameter x has been defined as the fraction of the RF absorption rate attributable to the electric exposure field; 1 - x is the fraction attributable to the magnetic exposure field. x depends slightly on frequency and subject. The results for all subjects exposed in an E orientation, and for all frequencies from 13.56 to 40.68 MHz, may be summarized as follows. For free space, $\bar{x} \pm SE = 0.93 \pm 0.04$ (13) and $0.7 < x < 1.1$ (except for one higher value). For the grounded case, $\bar{x} \pm SE = 1.01 \pm 0.01$ (15) and $0.9 < x < 1.1$. These results should not be extended to frequencies outside the range used, nor to wave impedance values outside the range of $0.5 < \eta < 2$.

The result that $x \doteq 1$ for the E orientations is being employed in our human RF absorption studies (eq. [2]) to correct the data so that measurements taken with a wave impedance slightly different from that of free space will apply directly to free space exposure situations. This is accomplished by calculating the exposure power density as $E^2/377$ and not as E x H. These corrections amount to no more than 20 percent.

Comparison to Quasi-Static Theory

Massoudi et al [5] calculated the whole-body absorption rate for the prolate spheroidal conductor model of man. The calculation applies to quasi-static frequencies which are limited, for adult humans, to no more than 15 MHz grounded or 30 MHz in free space. Their theoretical result for the E orientations (their equation (10)) can be reformulated to be identical to (3). For the standard size of prolate spheroid (a = 0.875 m, a/b = 6.34, 70 kg) and standard conductivity (0.43 S/m) it can be shown that x = 0.87

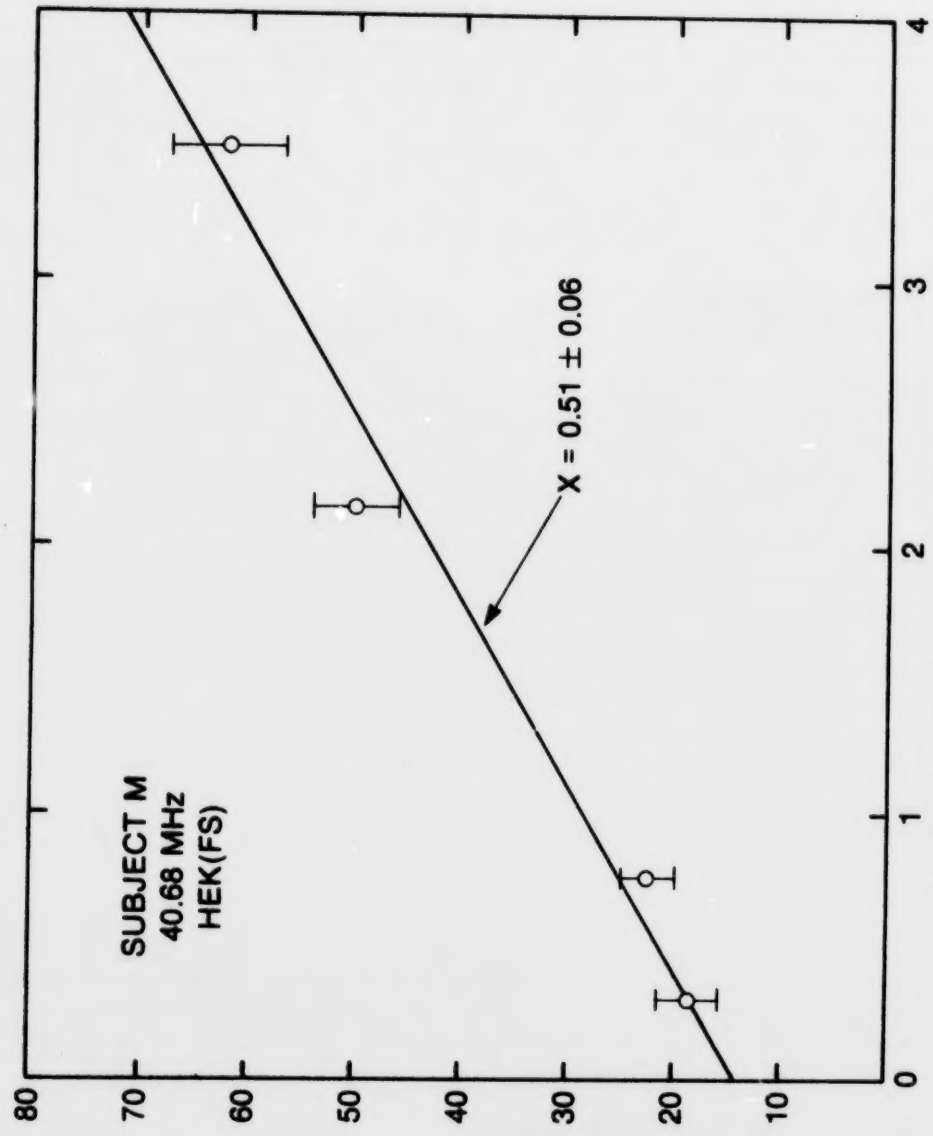

FIGURE 5 - WAVE-IMPEDANCE ANALYSIS OF THE FREE-SPACE ABSORPTION DATA FOR SUBJECT M IN AN HEK ORIENTATION AT 40.68 MHz.

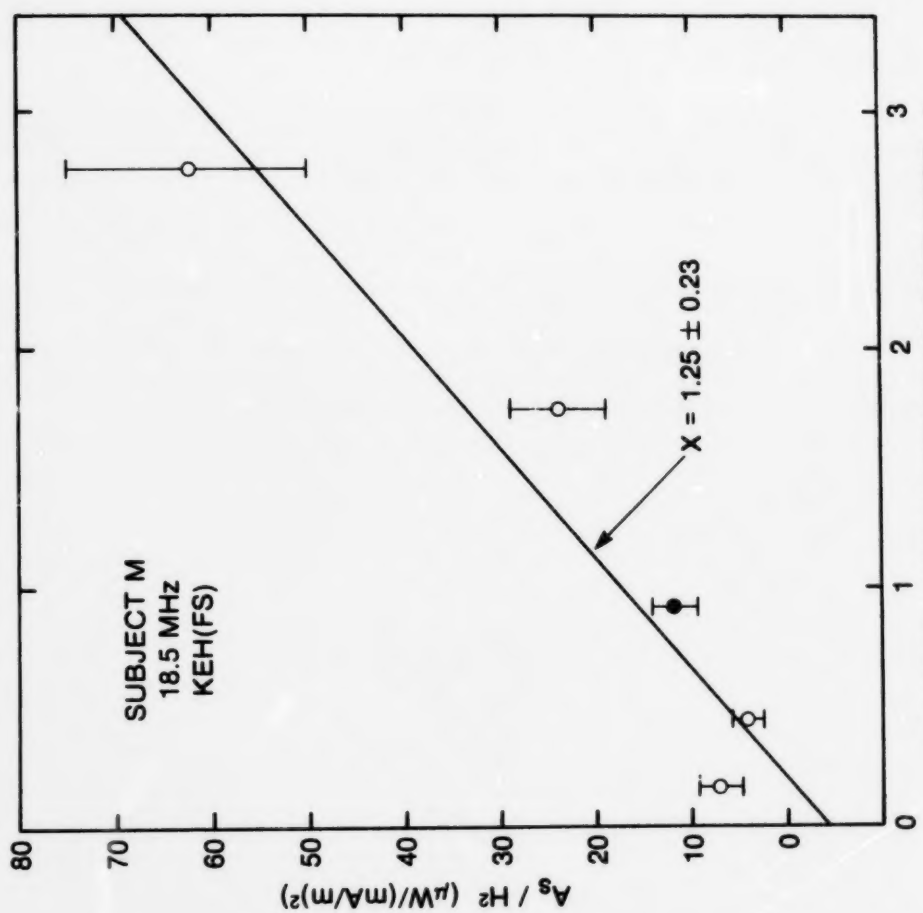

FIGURE 6 - WAVE-IMPEDANCE ANALYSIS OF THE FREE-SPACE ABSORPTION DATA FOR SUBJECT M IN A KEH ORIENTATION AT 18.5 MHz.

for free-space exposures at all quasi-static frequencies. The grounded case is modelled by the corresponding half prolate spheroid (a = 1.75m, a/b = 12.68) grounded, which gives a result of x = 0.98 for all quasi-static frequencies.

The above results for the standard model calculation are compared, in Table 3, to two non-standard model calculations and to the average human results. It can be seen in the table that the agreement between the free-space measurements and the theory is improved either by reducing the model's conductivity or by increasing its axial ratio. While the improvement in the value of x is modest, the non-standard model calculations are seen to also significantly improve the agreement with the measured absorption rates. The development of better models by either decreasing the model conductivity or increasing the axial ratio has been briefly reported by Hill [9] and will be discussed more fully in a future report.

In summary, our results for the wave-impedance effect on human E-polarization absorption rates are in good agreement with the only theoretical treatment of the problem - the prolate spheroid model calculation.

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TABLE 3

COMPARISON OF MEASURED AND CALCULATED HUMAN
E-POLARIZATION ABSORPTION RATES AT QUASI-STATIC FREQUENCIES

CONDUCTIVITY	AXIAL RATIO	WAVE-IMPEDANCE PARAMETER, x		NSAR[a] AT 13.56 MHz (% OF MEASURED FOR SUBJECT M)	
(S/m)	(a/b)	Free Space	Grounded	Free Space	Grounded
Prolate Spheroid Conductor Model					
0.43	6.34	0.87	0.98	33	22
0.25	6.34	0.95	0.99	47	31
0.43	8.0[b]	0.95	0.99	58	43
Human Measurements[c,d]		0.95 ±0.05(11)	1.02 ±0.02(4)	100	100

a. NSAR = Normalized Specific Absorption Rate ($mW.kg^{-1}/mW.cm^{-2}$).

b. a = 0.94m, b = 0.118m, mass = 55 kg.

c. Average of all quasi-static data in Tables 1 and 2.

d. The average ((EKH ± EHK)/2) NSARs for subject M at 13.56 MHz are 10.4 and 108 $mW.kg^{-1}/mW.cm^{-2}$, for free space and grounded, respectively.

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